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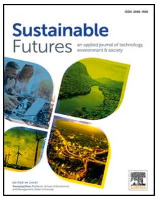

Toward sustainability and resilience with Industry 4.0 and Industry 5.0

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ABSTRACT

Digitalization and Industry 4.0 concepts promise substantial improvements in productivity and coordination, their adoption across the entire project lifecycle remains sporadic and incomplete in the construction industry. This digital divide not only hampers current performance but also poses a significant barrier to the industry's future competitiveness and sustainability. This study addresses a critical research gap by evaluating the comprehensive integration of digital twin technology from early design through project delivery in construction. Through an extensive literature review, we examine digital twin applications in the built environment and construction sector. Unlike previous studies focused on isolated use cases, our research provides a holistic assessment of digital twin implementation across all project stages. This study identifies key opportunities for digital twin to enhance collaboration, data sharing, and innovation in traditionally fragmented construction processes. The findings reveal that creating and populating digital twin from project inception enables more coordinated information flows and decision-making. This approach facilitates improved asset quality, sustainability outcomes, and stakeholder integration compared to conventional methods. By elucidating the full life-cycle potential of digital twin in construction, this study makes a novel contribution to both research and practice. The study also indicates that digital twin adoption aligns with and enables industry sustainability goals, though further research is needed to quantify these impacts. This work provides a foundation for future studies on optimizing digital twin implementation to transform construction productivity, quality and environmental performance.

1. Introduction

The construction industry is at a critical juncture, facing significant challenges that demand innovative solutions. These challenges include the urgent need for improved environmental sustainability, enhanced operational efficiency, and increased productivity. While many industries have been transformed by information technology and digitalization over recent decades, the construction industry has lagged in adopting these transformative technologies [1]. This slow adoption and the industry's fragmented nature have contributed to its lack of competitiveness and operational inefficiencies [2]. Digital twin technology has emerged as a promising solution to address these multifaceted challenges. Already widely used in manufacturing for modelling, simulation, and optimization [3], digital twin are gaining traction in urban planning and smart city development. The digital twin of cities and national environments is anticipated to revolutionize the built environment, enabling real-time data analysis and testing complex systems before physical Construction [4].

Despite growing interest in digital twin across various aspects of the built environment, there remains a significant gap in the comprehensive study of this technology for the entire construction process [5]. This gap is particularly notable when considering the potential of digital twin to integrate the many stages and stakeholders involved in construction, from early design to project delivery. Several key factors underscore the timing and necessity of this review. Rapid technological advancement demands an urgent assessment of emerging technologies' impact on Construction [6]. The industry's transition to Construction 4.0 necessitates a thorough understanding of how digital twin can facilitate this digital transformation. Increasing focus on environmental issues requires critically evaluating digital twin potential to optimize resource use and improve energy efficiency. The fragmented nature of the construction industry calls for innovative approaches to integration, which

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digital twin may provide. Lastly, while studies exist on digital twin in specific areas, there is a lack of comprehensive research linking these disparate fields across the entire construction lifecycle.

This study aims to investigate the reliability and effectiveness of digital twin technology as a means to enhance productivity, efficiency, and sustainability in construction and the built environment [5]. By evaluating the potential of digital twin to integrate various stages and stakeholders in the construction industry to provide a comprehensive assessment of how this technology can address fundamental sector challenges [7,8]. This research is motivated by the need to overcome longstanding issues in the construction industry and explore how digital technologies, particularly digital twin, can drive improvement and innovation [2]. The study intent to bridge the gap between analyses of digital twin in urban planning, construction sites, and site logistics, and research on digital twin for the built environment, intelligent buildings, and smart cities. This comprehensive review aims to contribute significantly to the ongoing digital transformation of the construction sector by synthesising current knowledge, identifying key trends, and highlighting future research directions. It will provide valuable insights for both academics and industry practitioners, potentially paving the way for more efficient, sustainable, and innovative construction practices. As the industry stands on the brink of a digital revolution, this timely review will serve as a crucial resource for understanding and leveraging the transformative potential of digital twin technology in construction.

The paper is structured as follows: Section 2 outlines the research methodology, while Section 3 presents the study's findings. The conclusion is presented in Section 4, which also discusses the results and their management implications. Finally, Section 5 offers recommendations and outlines directions for future research in this field. This structure provides a comprehensive overview of the study, from its methodological approach through its findings, conclusions, and future perspectives.

2. Methodology

This study meets the criteria for a systematic review [9]. A scientific procedure that can be replicated, known as a systematic review, is used to locate, select, and assess all published research pertinent to a given quality level [10]. One of the benefits of utilizing this methodology is that it makes it possible to research a particular area using a more logical and standardized technical approach [11]. As a result, the results can be presented to readers objectively and transparently [12]. There are some problems with the technique. Because journals tend to publish publications with findings that have a substantial influence, valuable studies with outcomes that are not significant, as well as articles written in a language other than English, will be overlooked [11]. The outline of this thorough systematic review may be seen in Fig. 1.

In accordance with the guidelines for conducting a systematic review [9,11], this review: (1) utilizes a systematic method to analyze a certain quality and number of studies on the topic of digital twin and construction 4.0 in New Zealand; (2) provides readers with an objective, transparent, and standardized technical roadmap, which includes information on the selection of databases, study retrieval, and the selection criteria of the target studies; (3) is both replicable and updatable; The primary components of this methodical strategy are as follows: (1) the framing of a question; (2) the collecting of relevant studies; (3) the selection and assessment of relevant studies; (4) the content analysis of relevant studies; and (5) the reporting of the results and conclusions [11].

2.1. Search strategy and the selection of studies

A search of the databases was performed every month, beginning in January 2023 and continuing through July 2023, using the same search technique. The terms "title," "abstract," and "keywords" were used as the criterion for Scopus with keyboard "Digital Twin OR "Digital Twins" AND "Construction industry" OR "BIM". When conducting research, one should search to locate as many relevant studies as feasible. The initial retrieval consisted of us collecting from each of the three databases any studies associated with implementing digital twin in the construction industry. We applied certain filters to the results in the second iteration of the retrieval process. As a result, there is a need for more investigation and development of digital twin and construction 4.0 research in New Zealand. After two separate rounds of data retrieval, two researchers carefully examined each of the remaining articles independently, paying particular attention to the papers' titles, abstracts, keyword lists, and body text. In order to narrow down the number of publications considered, we employed both inclusion and exclusion criteria [11]. The requirements were as follows: (1) any duplicated literature should be deleted; (2) any literature that was unrelated to the subject matter of implementing digital twin in the construction industry should be deleted; and (3) any literature that mentioned the idea of a digital twin but did not investigate it in depth should be deleted. A presentation of the first search in the Scopus database is displayed in Table 1.

A list of articles, book chapters, and conference papers are the result of the first search. The search was therefore limited to only "article" for Insight. Thus, 142 publications were kept as articles following the initial purifying procedure, as seen in Table 2.

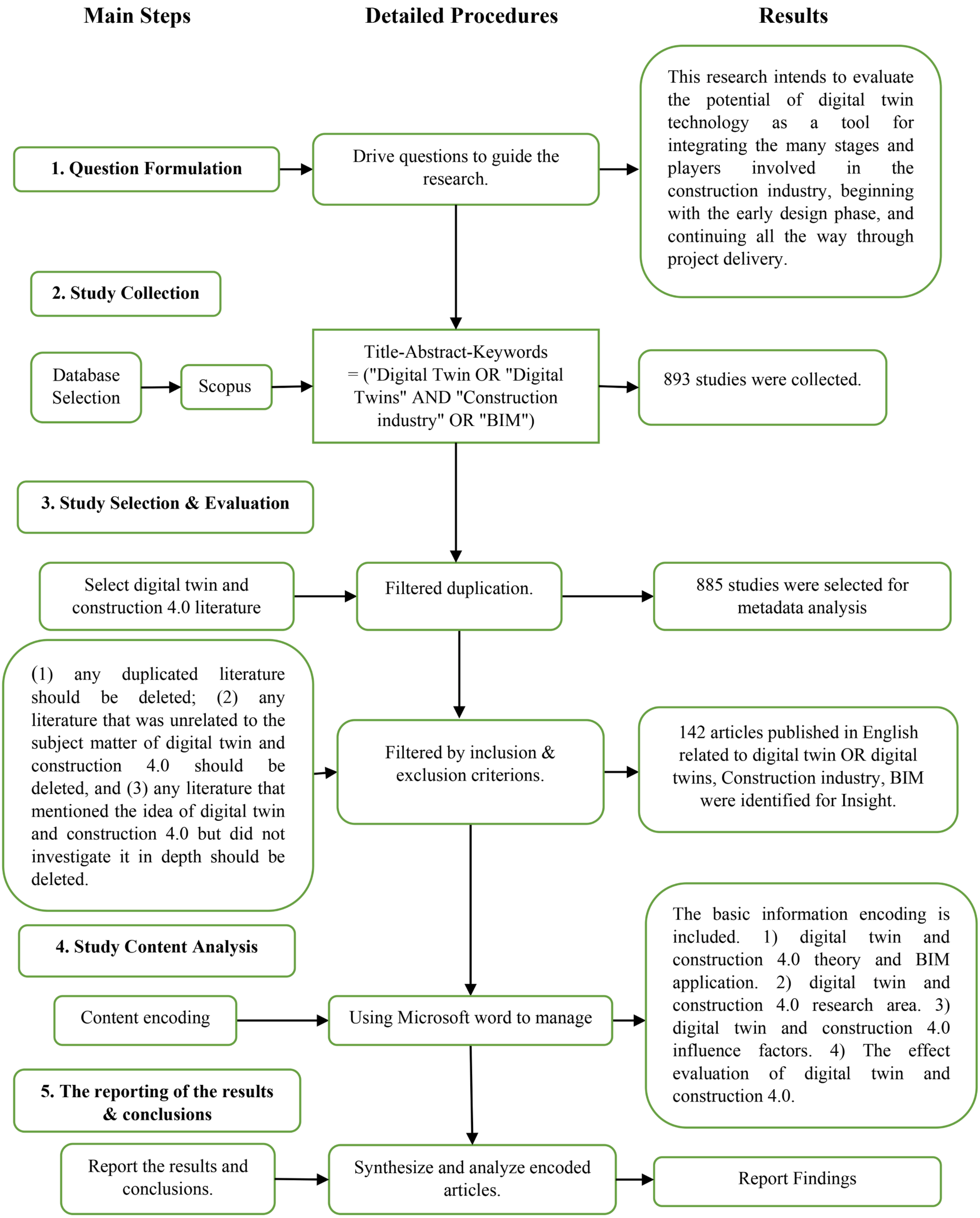
2.2. Content analysis

The study team studied the topic clusters to examine the articles' contributions to the growth and feasible future content trends in New Zealand. The team discovered, via reading the 142 chosen publications, that the study encompassed a wide variety of subjects, including the following: Some examine the application of digital twin to construction 4.0, supply chain management, and other study fields, while others present the concepts, principles, technologies, and methodologies associated with digital twin and construction 4.0 [11,13]. While others examine the efficacy of digital twin, some discuss the elements that influence the application of implementing digital twin in the construction industry [2,14]. Reading the titles, abstracts, and keyword lists of the 142 articles that were chosen led to their encoding. The complete text had to be read and encoded if the necessary information could not be gleaned from the article's title, abstract, or keywords. These articles were managed using Microsoft Word [15,16]. Articles related to the same subtopic were compiled onto a single page, and the articles' subtopics were colour-coded according to the category to which they belonged. Following the in-depth analysis of all 142 articles by hand, we determined four distinct subject matter groups. The coding mainly concentrated on the fundamental aspects of the literature's substance and information. (1) the paper's title, (2) the author's name, (3) the publication date, and (4) the title of the journal the article was published in were the fundamental pieces of information that were encoded. The subjects that were discussed in the research literature were classified into the following four groups: (1) digital twin theory and application; (2) implementing digital twin in construction industry research domains; (3) digital twin influence factors; and (4) the effect assessment of digital twin. It is essential to verify that the coding and classification are consistent to guarantee the content analysis's accuracy [17]. As a result, in this study, a scholar with substantial research expertise in implementing digital twin technology in the construction industry led a training session that included both a systematic training component and coding activities for two coders.

3. Findings

3.1. Metadata analysis and observations

The following section presents a comprehensive metadata analysis and its valuable insights. The analysis is based on 885 publications, which were carefully examined to extract critical information and



This research intends to evaluate the potential of digital twin technology as a tool for integrating the many stages and players involved in the construction industry, beginning with the early design phase, and continuing all the way through project delivery.

(1) any duplicated literature should be deleted; (2) any literature that was unrelated to the subject matter of digital twin and construction 4.0 should be deleted, and (3) any literature that mentioned the idea of digital twin and construction 4.0 but did not investigate it in depth should be deleted.

142 articles published in English related to digital twin OR digital twins, Construction industry, BIM were identified for Insight.

The basic information encoding is included. 1) digital twin and construction 4.0 theory and BIM application. 2) digital twin and construction 4.0 research area. 3) digital twin and construction 4.0 influence factors. 4) The effect evaluation of digital twin and construction 4.0.

Fig. 1. Methodology Framework.

Table 1
Initial Search Results and the Number of Papers Appeared for Metadata Analysis.

Search engines and database	Keywords	Results (no. of articles)	Limit to	Document type
Scopus	*Initial search result* "Digital Twin OR "Digital Twins" AND "Construction industry" OR "BIM"	**885**	Title, abstract, and the keywords	Conference papers, books, book chapters, editorial and articles

Table 2
The Result After Refining the Initial Search for Insight.

Keywords	Results (no. of articles)	Limit to
Deleting duplicates Scopus	**142**	Title, abstract, and the keywords
Criterion	**Inclusion**	**Exclusion**
Timeline	2017 – 2023	Earlier than 2017
Document Type	Articles, Review article, Conference	Proceeding and Book, Editorial
Language	English	Non-English

trends. Understanding the implications of digital twin technology in the construction industry in this analysis is crucial to accurately interpreting the findings. In cases where a manuscript has multiple authors, each author is counted individually during the metadata analysis. This approach ensures that every contributor receives proper recognition for their work.

Similarly, the respective nations and institutes of the authors also receive one publication credit each. This allows for a comprehensive analysis of the geographic distribution of research and the identification of leading institutions in the construction industry field of digital twin technology. The analysis provides a holistic view of the research landscape by assigning credit to both authors and their affiliated institutions. It is important to note that the specific statistical findings presented in this study are summarized rather than presented as an exhaustive list. This approach enhances the readability and clarity of the analysis, making it more accessible to a wider audience. The study highlights the key trends and insights that emerged from the metadata analysis by focusing on the most significant and relevant findings.

3.1.1. Publications by year

This study's time analysis serves two primary purposes: examining the temporal trend of research on digital twin technology in the construction industry and identifying key factors influencing these trends. By analysing publication dates, researchers can gain insights into the evolution of research approaches and shifts in focus over time. This analysis helps identify periods of increased research activity and the development of the field. The second objective is to pinpoint specific events, advancements, or societal changes that have shaped the direction and intensity of digital twin technology research in construction. These factors may include technological breakthroughs, policy changes, or increased public awareness.

Researchers systematically organized and examined 885 papers from the Scopus database to accomplish these objectives. The papers were stored in an Excel file and arranged chronologically based on publication dates. Fig. 2 presents a graphical representation of the number of papers on digital twin technology in construction published yearly from 2017 to 2023. This visual representation enables researchers to identify patterns, trends, and significant changes in research output over the past seven years. The temporal analysis provides valuable insights into the growth and evolution of digital twin technology research in the construction industry, offering a foundation for understanding current trends and predicting future directions in this field.

3.1.2. Publications by institutions

Fig. 3 visually represents the interconnections among researchers who have contributed to the field of digital twin technology in the construction industry. This network analysis highlights the collaborative nature of research in this domain and illustrates the connections formed by authors from various institutions. Among the institutions featured in the analysis, the Ministry of Education of the People's Republic of China emerges as the leading contributor, with an impressive total of 40 publications. This substantial output demonstrates the institution's strong commitment to research in digital twin technology for construction and solidifies its position at the forefront of this field.

The University of Cambridge also exhibits noteworthy contributions, with 22 papers on the subject. This achievement underscores the global nature of research in digital twin technology and highlights the valuable insights coming from researchers with diverse geographical and cultural backgrounds. Following closely, the Politecnico di Milano has made significant contributions to the field, with 18 publications. This high number of publications reflects the institution's strong presence and expertise in construction technology research. The collaborative networks revealed by this analysis demonstrate the interdisciplinary and international nature of digital twin technology research in construction. These connections facilitate the exchange of ideas and methodologies, potentially accelerating advancements in the field.

3.1.3. Publications by authors

The authors have identified the most influential and productive researchers in the construction industry's digital twin technology field. Fig. 4 presents the top ten most productive academics, ranked based on their overall career output in terms of published papers. As depicted in Fig. 4, Kaewunruen, S., Liu, Z., and Lv, Z. emerge as the most prolific authors, each contributing ten papers to the analyzed articles. This

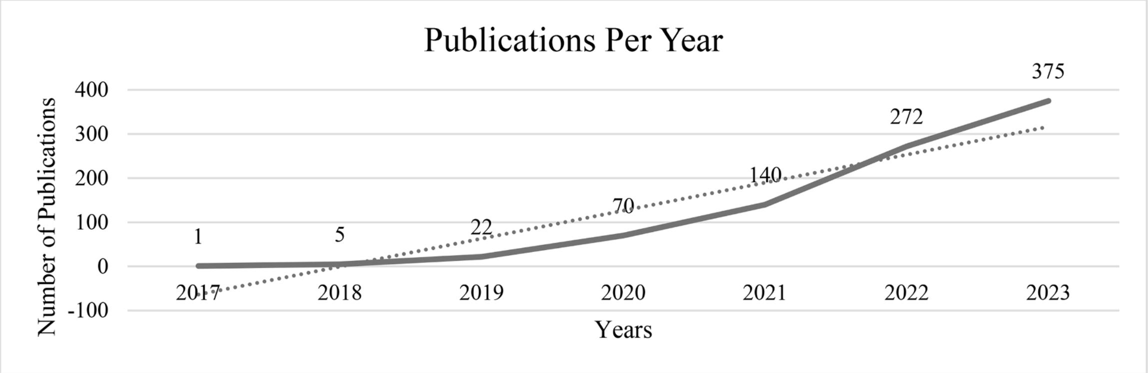


Fig. 2. Number of Publications Per Year.

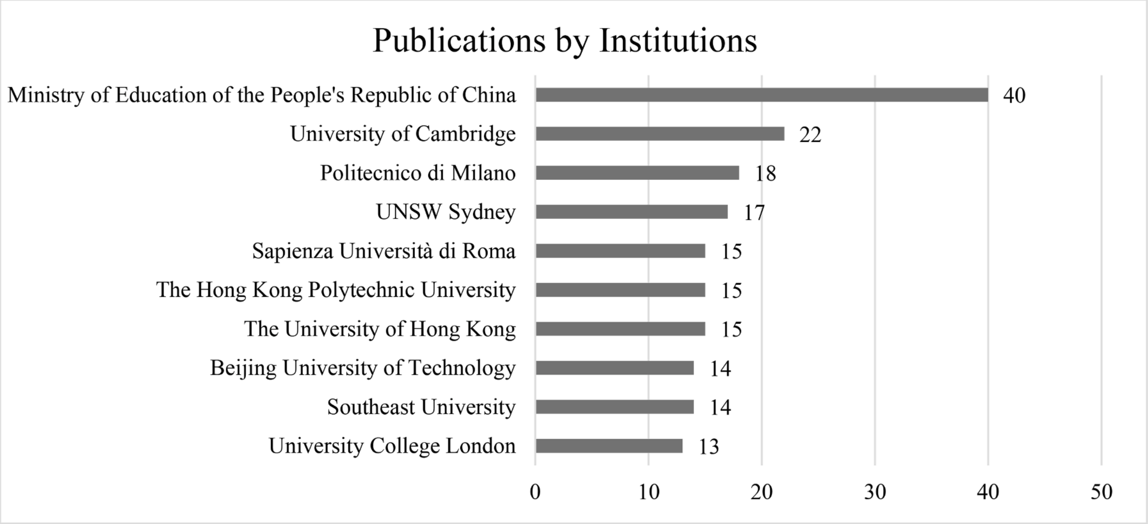


Fig. 3. Top Ten Institutions by Publications.

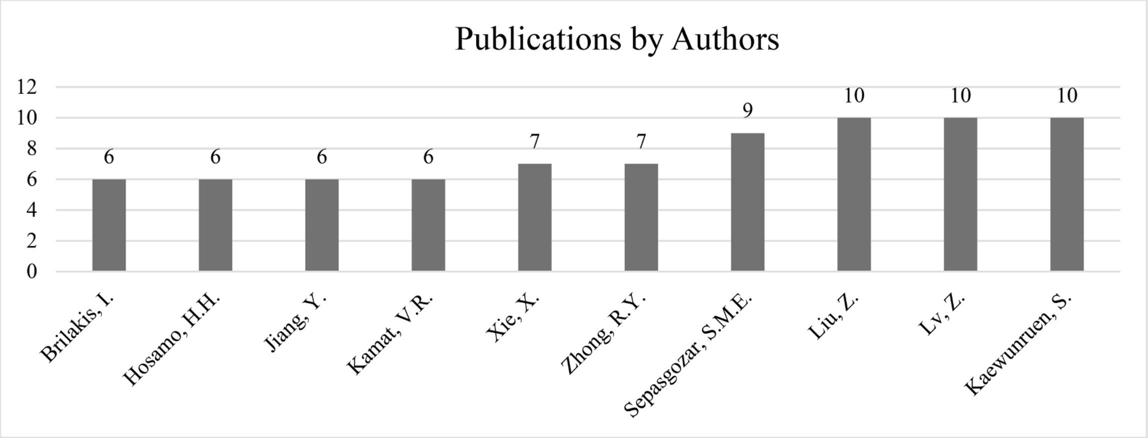


Fig. 4. Top Ten Authors.

achievement demonstrates their extensive expertise and dedication to advancing the understanding of digital twin technology in construction. Their research has likely provided valuable insights and innovative approaches to the field, establishing them as leading figures in this study area.

Following closely behind, Sepasgozar, S.M.E. and Xie, X. are listed as the fourth and fifth most productive authors, contributing 9 and 7 articles, respectively. Their substantial involvement and commitment to digital twin technology in construction is evident through their consistent output. Their diverse publications indicate broad knowledge and an ability to explore various aspects of technology in the construction industry. This analysis highlights the significant contributions of these researchers to the field, showcasing the depth and breadth of expertise driving advancements in digital twin technology for construction applications.

3.1.4. Publications by countries

This study analyzed the global distribution of research and application of digital twin technology in the construction industry. The aim was to identify regions with significant interest and activity in this field. We categorized each of the 885 papers based on the countries mentioned in their abstracts and then grouped these countries by continent. This approach allowed for a focused analysis of digital twin technology in construction within the subset of papers.

Fig. 5 illustrates the global distribution of publications on digital twin technology in construction. The figure indicates the number of papers each country publishes on this topic. China emerges as the leading contributor, with 312 articles published. The United States closely follows with 110 publications, while the United Kingdom ranks third, publishing 107 articles. Italy secures the fourth position, contributing 64 articles to the literature on digital twin technology in construction. Australia and Spain rank fifth and sixth, with 54 and 36 papers, respectively. This distribution highlights the global nature of research in this field, with significant contributions from various countries across continents.

3.1.5. Publications by journals

Automation in construction emerged as the leading publication outlet, contributing 49 out of 885 articles reviewed on digital twin technology research. Buildings followed closely with 48 articles. Applied Sciences Switzerland and Sustainability Switzerland also contributed significantly, publishing 41 and 37 articles (Fig. 6).

3.2. Construction 4.0: revolutionizing the built environment

According to Popkova & Zmiyak [18], the initial phases of the fourth industrial revolution, often known as Industry 4.0, are now being played out across a variety of business sectors throughout the world. According

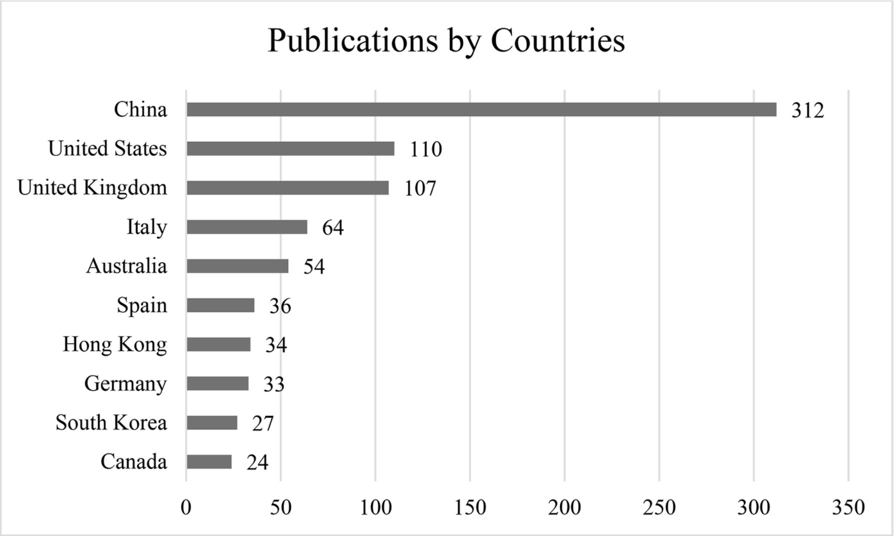


Fig. 5. Top Ten Countries.

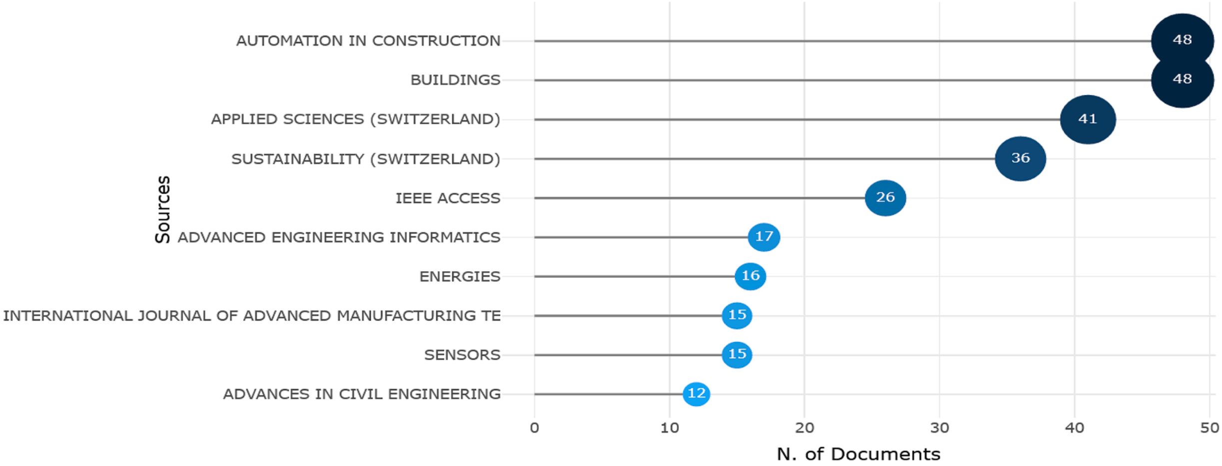


Fig. 6. Publications by Journals.

to Khan et al. [19], the fourth industrial revolution, also known as Industry 4.0, is characterized by its heavy reliance on digitalization and its utilization of big data and process automation. This contrasts the previous three industrial revolutions, which also introduced new technology. According to Popkova & Zmiyak [18], the fourth industrial revolution, also known as Industry 4.0, is distinct from other revolutions in several unheard-of aspects, such as eliminating human involvement and manual decision-making from the processes involved. According to Bonnet & Westerman [20], the automation of processes is essential to the success of Industry 4.0. According to Qi et al. [21], the evolution of digitalization has moved through the phases of digital enablement and digital support, and it is now positioned to enter the stage of digital control, connecting and combining the physical and digital worlds. This figure illustrates the key components and relationships within the concept of Construction 4.0, which represents the construction industry's digital transformation. The diagram is organized into four main sections that interact with and influence each other: Construction 4.0 Requirements, Construction 4.0 Technologies, Construction 4.0 Lifecycle, and Construction 4.0 Interaction. At the core of the diagram are the Construction 4.0 Technologies, which are the driving forces behind this industrial revolution in construction. These technologies include Autonomous Robots, Simulation, System Integration, Internet of Things (IoT), Cybersecurity, Cloud Computing, Additive Manufacturing, Augmented Reality, and Big Data & Analysis. Each of these technologies plays a crucial role in modernizing and optimizing construction processes, from design and planning to execution and maintenance.

The circular arrangement of these elements suggests that they are interconnected and interdependent. For instance, the Internet of Things may generate vast amounts of data, which can then be processed and analyzed using Big Data techniques. Similarly, Simulation and Augmented Reality might work in tandem to create more accurate and interactive project visualizations. The inclusion of Construction 4.0 Lifecycle implies that these technologies and practices are applicable throughout the entire lifespan of construction projects, from conception to completion and beyond. This holistic approach ensures that the benefits of Construction 4.0 are realized at every project stage. The Construction 4.0 Requirements section likely refers to the fundamental needs or prerequisites for implementing these advanced practices and technologies. This could include factors such as digital literacy, infrastructure readiness, or regulatory compliance.

The Construction 4.0 Interaction component suggests that there is a dynamic interplay between all these elements. This interaction is crucial for successfully implementing Construction 4.0, as it requires the seamless integration of various technologies and processes across different stages of construction projects and among various stakeholders (Fig. 7).

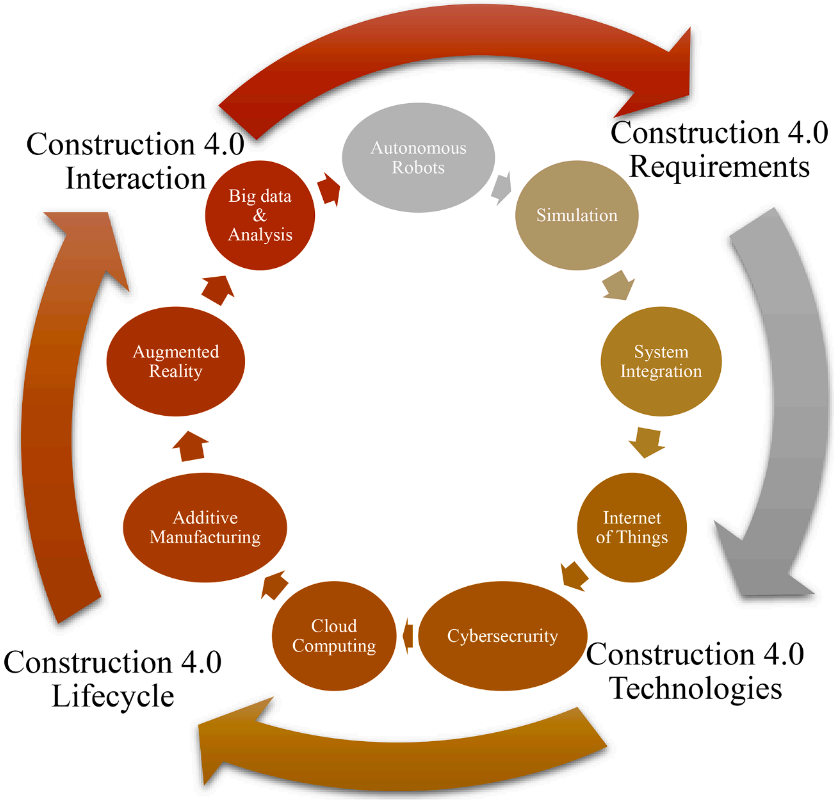


Fig. 7. Construction 4.0 with Digital Twin.

This figure effectively encapsulates the essence of Construction 4.0 by highlighting its key technologies, their lifecycle application, the necessary requirements, and the interaction between these elements. It provides a comprehensive overview of how digitalization and advanced technologies reshape the construction industry, promising increased efficiency, productivity, and innovation. This framework in support of Construction 4.0 was presented by Sawhney et al. [22]. Sawhney et al. [22], introduced a framework supporting Construction 4.0, applying Industry 4.0 concepts to the construction sector. This framework utilizes a digital twin as an interface between Construction 4.0 and digital twin layers. The authors define Construction 4.0 as a paradigm that uses cyber-physical systems, the Internet of Things, Data, and Services to link digital and physical layers, creating an interconnected environment for efficient asset management. Understanding the technologies facilitating this change is crucial for comprehending the layers of Construction 4.0 [23]. Nine key technologies frequently mentioned in current research include Augmented Reality (AR), Virtual Reality (VR), Integrated Building Information Modelling (iBIM), Robotics, 3D Printing, Artificial Intelligence (AI), Unmanned Aerial Vehicles (UAVs), Internet of Things (IoT), and Big Data. Integrating Construction 4.0 technologies occurs at two levels: a lifecycle perspective and enhanced communication. The lifecycle perspective involves incorporating technologies throughout a project's lifecycle, from planning to facility management [24]. Enhanced communication focuses on improving interaction among Construction 4.0 technologies [8].

The shift to Construction 4.0 represents a significant paradigm shift in the building process [25], requiring changes in thinking and techniques. Key considerations include adapting digital technologies to construction industry needs, employee training for new roles, incorporating new technologies across various projects, shifting from project-oriented to process-oriented perspectives, and digitizing existing procedures. Sawhney et al. [22], present a comprehensive Construction 4.0 framework based on Industry 4.0 principles. The digital layer acts as an interface linking multiple physical layers through digital tools, establishing a robust connection between the physical and digital worlds. Building Information Modelling (BIM) and Common Data Environments (CDE) play crucial roles in developing digital twin [26]. These digital layers support not only the design and construction of assets but also facilitate downstream activities throughout an asset's entire lifecycle, including demolition [27]. The transition to Construction 4.0 necessitates a change in both thinking and techniques, presenting challenges and opportunities for the construction industry.

3.3. *Role of technology in the construction industry*

In order to conduct an efficient investigation into the management of companies, it is necessary to consider the part that technology plays and critically reflect on that part [7,28]. This function of technology may shift in accordance with various theoretical frameworks of technology. Orlikowski & Scott [7], stated that the constructive intertwining of organisational activity is usually done in some specific situations. As a result, it is impossible to comprehend technology apart from its context, meaning, and consequence. Concepts ought to be fluid and often change to keep pace with both the progression of technology and the application sector [29,30]. This will ensure that no intentionality or qualities are ascribed to technical creations. Since it has not been conceptualized yet how work in organizations is connected to technology, a more sophisticated theoretical lens will need to be developed over time. This table provides a concise overview of the key technologies in Construction 4.0, their roles, and their benefits to the construction industry (Table 3).

In order to grasp the integrated, multifaceted, and ever-evolving function of technology, it is likely necessary to draw from various technological views and conceptual frameworks. Gunderson [28] says that in the same manner, technology can turn out to be less noticeable as time passes or as it becomes an increasingly fundamental part of society. Consequently, theories of the influence and interaction of technology give insights to explore and frameworks within which to partially think, even though the technology is not expressly recognized to be connected

Table 3
Role of Technology in Construction.

Technology	Role in Construction 4.0	Benefits
Autonomous Robots	Perform complex tasks and imitate human behaviors	Increased efficiency, reduced labour costs, improved safety
Simulation	Virtual testing and optimization of processes	Better planning, reduced errors, and cost savings
System Integration	Connect various technological systems	Seamless operations, improved data flow
Internet of Things (IoT)	Create a dynamic network of interconnected devices	Real-time monitoring, predictive maintenance
Cybersecurity	Protect digital assets and data	Reduced risk of data breaches, enhanced trust
Cloud Computing	Enable remote data storage and processing	Improved collaboration, scalability, cost-effectiveness
Additive Manufacturing (3D Printing)	Create sophisticated 3D objects from CAD models	Rapid prototyping, customization, reduced waste
Augmented Reality (AR) and Virtual Reality (VR)	Provide immersive experiences and information visualization	Enhanced training, improved design visualization
Big Data & Analysis	Process large amounts of data to derive insights	Better decision-making, performance optimization
Building Information Modeling (BIM)	Provide a model-centric approach with 3D visualization	Improved coordination, clash detection, lifecycle management

to organizational activities [31]. According to this concept, technology should, in and of itself, be regarded as something more than just technological objects. It makes a difference in how it was used and for what purposes. In addition, the digital twin may be viewed as having an influence, impact, and interaction with the organization's activity, and it can only exist in connection to present or future building methods and procedures. According to Orlikowski & Scot [32], the influence and interaction of technology are frequently the driving forces for the concentration on technology in organizational research. According to Gunderson [28], technology influences not just the interaction of organizations with one another but also the interaction of societies with the built and natural environments in which they live. Even though the digital twin is intertwined with situational practices, it is possible that organizational activity involving the construction industry does not yet include it as an essential component.

Peine [33], claims that a technological paradigm can describe certain aspects of technological development in response to certain situations, but it cannot explain the innovation process as a whole. It is a technological paradigm described by Peine [33], as a dominating design, mutual obligation, and mentality. This definition is derived from scientific paradigms, which are expected answers to a problem that all parties generally accept. The technological paradigm can largely depict the cumulative technical progress within an industry if the dominant design has been properly established throughout that industry. Nonetheless, achieving coordination about a common commitment and mentality is more challenging. Cantwell & Hayashi [34], characterize the technological paradigm in a manner that is analogous to that of Peine [33]. They define it as the commonalities found in a cluster of discoveries and efforts to innovate that occur throughout time and within an age in which scientific principles and organizational practices are comparable. The best description of social evolution and the innovation process is exemplified in the paradigm changes and the integration of major aspects of technology and innovative types of information, institutions, and production factors. According to Cantwell & Hayashi [34], these technological, socioeconomic, and political paradigms may be implemented in the manufacturing sector, technological domains, or in society.

3.4. Digitalization level in the construction industry

There is an obvious distinction in the construction industry at the moment between businesses that have transitioned to digital processes and technologies. Examples of such are Building Information Modelling (BIM), Tekla, and other CAD-related applications, as well as others that continue to rely on more conventional strategies. According to Ayinla & Adamu [35], this "digital divide" may be ascribed to several different constraints and limits that organizations confront while attempting to implement digitalization. This process may be prompted by demands or requirements imposed from the outside by customers, project owners, or the government. According to Bosch-Sijtsema et al. [36], governments have become increasingly mandating the use of BIM, particularly for more significant contractors, and as a format of delivery, which has led to an increase in the amount of digitalization in projects [30].

On the other hand, SMEs have transitioned to adopting BIM more gradually. This supposed value of BIM is the primary factor in determining whether or not it is implemented [36]. Actual users find great value in the technology and advocate for its usage, but non-users do not see the value to the same degree. In addition, implementing BIM affects small and medium-sized enterprises (SMEs), which do not have the means to invest in BIM technology to the same degree that bigger actors may, despite the development of rules that enhance the necessity of BIM. According to Dainty et al. [37], the expenses of training and software are two of these obstacles. According to Ayinla & Adamu [35], organizations' ability, particularly those established upon "innovation thinking" as a driving force, is a critical component in determining the impact of these elements. According to Dainty et al. [37], the "digital divide" is particularly common within bigger organizations, where certain workers are influenced by the barrier of BIM's motivational and skill requirements.

According to Davies & Harty [38], an individual's readiness to embrace BIM is connected to their perceived opinion of whether or not they believe BIM may benefit them in their line of work. Employees will decide whether or not to embrace BIM based on their newly acquired knowledge of what defines performance in their present function and how the implementation of BIM will either improve or degrade that performance [39,40]. Even among those adopting digital tools, there is still a variance in the extent of actual digitalization, with some organizations believing that simply switching from physical to digital documents is sufficient to meet their requirements for digitalization. However, the digital transformation of the industry entails a far more complicated set of circumstances, and for organizations to attain saturation, there is a requirement for both internal and external pressure to adapt for them to evolve [41,42]. According to Bosch-Rekveldt et al. [43], the construction industry is distinctive in several respects. For example, it has a project-based structure, in which individual construction projects function virtually identically to independent businesses, and the completion of huge construction projects can take decades. In an organization structured from the top down, project leaders fulfil a function analogous to that of the CEO. The construction business is considered to have a vertical structure, in contrast to the horizontal structures found in industries such as manufacturing, which results in restricted knowledge and data transfer across projects [29,44].

3.5. The idea of digital twin

The idea of digital twin is a very recent one, and it is one that is always being developed further. However, the idea has been utilized in different sectors since the 1960s, with its genesis in NASA's space missions [45]. Dr. Michael Grieves is credited with coining the "digital twin model" phrase in 2002. However, the concept can be said to have been applied in numerous industries since the 1960s. One way to explain a digital twin is to describe it as the combination of a physical object, its digital rend, and how both are connected despite the existence of a conventional definition of the digital twin. A real digital twin is accomplished when a bidirectional link exists between the two, giving an accurate and valid representation of the physical asset [46,47]. The degree of connectivity between the physical and digital products may vary depending on the application. Still, a true digital twin is obtained when a link exists between the two in both directions. The digital twin concept is particularly important in the construction industry because of its considerable potential benefits. Fig. 8 displays the concept of digital twin.

Fig. 8 illustrates the concept of a digital twin in the context of buildings or infrastructure, highlighting the crucial bi-directional connection between the digital and physical realms. On the left, a simplified wireframe building labelled "DIGITAL" represents the virtual model, while on the right, a more detailed, coloured building labelled "REAL" depicts the actual physical asset. Central to the image is a connection, symbolizing the interface through which this bi-directional interaction occurs. This bi-directional connection is fundamental to the digital twin concept and carries significant implications. Data flows from the real building to its digital counterpart, allowing the virtual model to be continuously updated with real-time information from sensors, IoT devices, and other monitoring systems. Conversely, the digital twin can influence the physical asset, enabling adjustments to build systems, predictive maintenance, and simulation of changes before real-world implementation. This dynamic, two-way relationship ensures that the digital twin is not merely a static model but an active, up-to-date representation that both reflects and influences the physical asset.

The connection emphasizes that users can interact with both the digital and physical versions of the building through a common interface. This integration facilitates comprehensive management and analysis, leveraging the power of digital twin for real-time monitoring, operational optimization, and informed decision-making based on current and simulated data. Ultimately, this bi-directional connection exemplifies the transformative potential of digital twin technology in revolutionizing how we design, construct, and manage the built environment.

According to Glaessgen & Stargel [48], "a digital twin is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product. This simulation uses the best available physical models, sensor updates, and other such things to mirror the life of its corresponding twin." According to Schroeder et al. [49], a cyber-physical system product lifecycle model represents a virtual real product that contains information on the product from the start of its lifecycle to its disposal. According to Leng et al. [50], the linked representation is a digital twin of the machine running in the cloud platform and imitating the health status based on combined data-driven analytical algorithms and other accessible physical knowledge. In their "Gemini Principles," the Centre for Digital Built Britain (CDBB) suggested two unique definitions of a digital twin, the first of which emphasized the model's dynamism and the second of which emphasized strategic importance. A dynamic model of an asset that receives current performance data from its physical twin in the form of live data flows from sensors and provides feedback to the physical twin in the form of real-time control [51,52]. A system model for the system's static strategic planning gives a reaction to the physical twin through the capital investment process using imputed long-term data from the physical twin via corporate strategies.

As the demand for enhanced efficiency and competitiveness in construction grows, adopting digital twin solutions becomes more prevalent [2]. This involves integrating various forms of Industry 4.0 technologies tailored to construction contexts [53]. In the following sections, we delve into implementing Industry 4.0 technologies relating to four basic features of the digital twin. These features comprise the acquisition of data, process of data, simulation and modelling, and decision support enablers [2].

Modelling and Simulation: Modelling and Simulation are fundamental components of digital twin technologies. Both utilise 3D high-fidelity models and simulations in order to provide detailed visualizations for the evaluation of some particular scenarios so as to validate automatically computed solutions. These aspects synergistically complement other construction-related technologies presented in Table 4.

Data processing: Data processing plays a crucial role in handling the vast amounts of real-time, diverse data collected. It involves converting and treating raw data to extract meaningful information for modelling and analysis purposes. Table 5 provides an overview of the enabling technological tools adopted in various scholarly works in addressing challenges peculiar to the construction industry.

Decision support enablers: Decision support is a critical aspect of construction systems, empowering them to handle disruptions and ensure smooth lifecycle transitions. Implementing semantic solution production using different tools and approaches is key to this capability, as outlined in Table 6. Emphasizing the significance of artificial intelligence (AI) in decision support, specific AI domains play a pivotal role in this context.

Data acquisition: the extraction of unprocessed data is initiated by the data acquisition process and concludes with the information transmission to a cloud-based server or database. In Table 7, we have outlined the key technologies along with their associated construction applications.

In the context of advanced construction, the process revolves around digitalizing assets and resources through a meticulous approach, transforming them into a virtual space [59,60]. This comprehensive digitalization entails acquiring data from multiple sources, real-time two-way connectivity for monitoring and control, and seamless cyber-physical information exchange. At construction sites, physical data is gathered using an array of sensors and communication devices, adhering to industrial communication protocols. Techniques like point cloud mapping and BIM modelling facilitate mapping this data onto cyber entities [69]. In the cyber component, various tools such as BIM, simulation, point cloud, and 3D models are employed to ensure accurate representation and simulation of construction activities [68,71]. The subsequent data processing and computational layers are vital in converting raw data into valuable information and knowledge. This is achieved by treating data, storage, retrieval, and modules relating to analytical processing. Data fusion and semantic modelling are utilized to seamlessly integrate

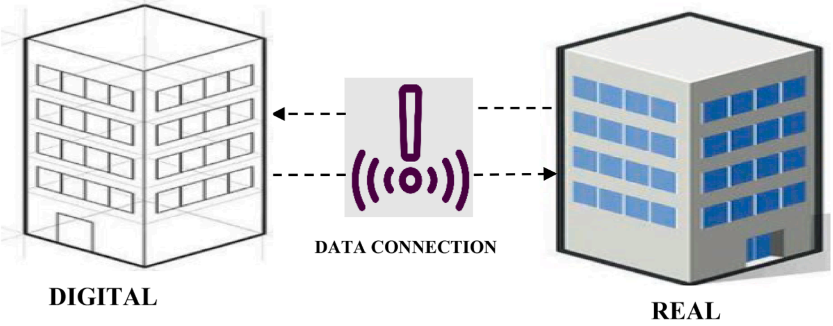


Fig. 8. Digital Twin.

Table 4
Modelling and simulation in Construction industry.

Technology	Construction Applications	References
Building Information Modelling (BIM)	To enhance structural health monitoring (SHM), it is vital to incorporate disaster planning and damage inspection capabilities. By integrating these aspects, the SHM system can better predict and respond to potential structural issues, ensuring safety and mitigating the impact of disasters.	[39,40]
	Building lifecycle management (BLM), comfort, and energy efficiency are all improved via facility management. Include decision support systems, maintenance work, and anomaly detection.	[54,55]
	Designing and optimizing assets. Automate construction-related productions by using configure-to-order and lean manufacturing strategies. Maximize the output of precast components. Establish sustainable behaviours.	[56,57]
Virtual/Augmented Reality	Partnership between humans and robots. Makes job planning and supervision easier through two-way communication and asset management.	[58]
	Design and planning of cities. Several perspectives and usability testing were done by individuals who were not experts in the construction process.	[58]
Point cloud	Visualization and design of assets. Creates city and building models utilizing as-built reconstruction techniques, gestalt design principles, and LiDAR. ML/DL-based point cloud interpretation is used to categorize models.	[29,44]
	It examines how well-established a structure is, predicts possible damage that may occur in a structure, and inspects services for digitized structures in a VR environment.	[29,30]
Simulation	Optimizing the design of a structure. Using parametric geometric modelling and high-resolution analysis, prototype development time and cost may decrease.	[41,42]
	Optimizing building performance. Activate infrastructure visualizations to monitor electricity and the environment.	[30]

Table 5
Data processing in the Construction industry.

Technology	Construction Applications	References
Data Mining	Management of projects. The development of greater automation and intelligence	[59]
	Optimizing building performance. Enhance the energy effectiveness for both old and new structures.	[60]
Blockchain	Create sustainable habits. Creates a blockchain-integrated intelligent platform to sustain built-up residential structures.	[61]
	Management of projects. Enhance efficiency by implementing contracts, stakeholder cooperation, and improved service.	[31]
Semantic Modelling	Designing and optimizing assets. Reconfiguration of equipment should be permitted to manage any form of interference. Locate a panorama that does not have less than one meter of localization error. Boost the representation of assets.	[62]

Table 6
Decision support enablers in the Construction industry.

Technology	Construction Applications	References
Machine Learning	Monitoring of construction equipment. Analyze how an asset performs under various circumstances.	[63]
	Maximizing on-site construction. Optimize building component structures and the construction process timetable.	[64]
	Control over safety. Create a DT-based interior safety management system as well as a security system for an elevator with three floors in a commercial building.	[65]
Computer Vision	Management of facilities, such as the renovation of 3D structures from CAD sketches and street view pictures, as well as movement recognition for maintenance activities.	[66]
	System for maintaining bridges. Image recognition is used to improve inspection procedures.	[67]

Table 7
Data acquisition in construction industry.

Technology	Construction Applications	References
Internet of Things (IoT)	Improving structural health monitoring (SHM). Infrastructure preventive maintenance should be included.	[68]
	Optimizing building performance. Include interior safety management, sustainability evaluation, energy efficiency, and an improved FM system in the BLM process.	[69]
Wireless Sensor Network	Enhance lifetime management and energy saving to reduce building costs.	[70]
	It uses cyber-physical systems in order to improve structural health monitoring (SHM)	[71]
Social Media	Boost the management of the construction lifecycle. Plan, design, construction, and usage elements are included.	[72]

multiple data sources and establish meaningful relationships between data nodes [72]. Core construction applications are located by the functional layer while incorporating domain-specific knowledge, including safety protocols, regulations, and stakeholder preferences [63, 67]. This knowledge is meticulously refined and presented to end-users through intuitive visualization interfaces. These interfaces empower users to interact with and manage physical assets while implementing system-generated solutions. By integrating these modules, specific construction challenges can be effectively addressed and overcome [65].

3.6. The transition from BIM to digital twin

Digital twin represents a comprehensive conceptual strategy that integrates various technological tools, including Building Information Modelling (BIM), to enhance decision-making processes within the sector. This approach leverages advanced technologies to create a virtual representation of physical assets, enabling more informed and efficient project management throughout the construction lifecycle [54, 55]. Building Information Modelling (BIM) is currently the most widely adopted digital modelling technology in the construction industry [73]. Initially used to produce 3D representations of assets, BIM has evolved significantly with the introduction of the Industry Foundation Classes (IFC) standard, enabling greater integration across platforms. A key advantage of BIM technology is its ability to provide a semantic 3D model that serves as a comprehensive database of asset data [74]. However, the integration of BIM data with other systems, including Internet of Things (IoT) devices, faces several technological, informational, and organizational challenges.

Despite the advancements in BIM technology and its evolution towards digital twins, significant challenges persist. Integration difficulties remain a key obstacle, preventing the seamless connection of valuable information and data with other systems. These barriers limit the full potential of digital modelling in construction, hindering the industry's ability to leverage data effectively across various platforms and processes [74]. Overcoming these integration challenges is crucial for realizing the complete benefits of digital twin technology in the construction sector. Camposano et al. [75], stated that to address the difficulties, the idea of a digital twin has recently surfaced as a potential option. The similarity of both BIM and digital twin makes it possible for them to give 3D visualizations of assets; however, digital twin provides higher complexity and integration possibilities since they focus on establishing a human-centric, useable platform.

The digital model is an extremely important component that enables many facets of the building and construction business. However, realizing the full potential of these features will require overcoming the limitations of BIM's integration capabilities. Because of this, creating more integrated platforms capable of integrating without any hitches with many other processes and systems is required [76]. The ultimate purpose of digital twin is to accomplish the most advanced degree of digital maturity that is humanly achievable. However, because no example of a digital twin has reached its complete potential, the notion of digital twin is not totally defined, making it challenging to ascertain whether a digital twin has reached its full potential [75]. In addition, the asset in and of itself to which a digital twin idea is applied greatly impacts the degree to which it has matured, seeing as how the use case determines maturity. Because there is no one agreed-upon meaning for the term, there are many distinct ways in which it may be interpreted. As a result, different stakeholders have differing expectations for the amount of connection they need and the information that must be sent to them. Therefore, it is essential to ensure that the deployment of digital twin is beneficial to all parties involved in the building business [76].

The value that the digital twin would eventually add would be the wealth of dynamic data it could handle, its meaning (semantics), and its ongoing knowledge accumulation regarding the physical world [77]. This would be the case since a digital twin would represent the physical world. This brings long-term benefits to the built environment because of the smarter and more efficient building process and smarter lifecycle management. A society becoming increasingly environmentally conscious would automatically lead to reduced lifespan costs, increased asset resilience, and decreased carbon emissions [77]. The government acknowledges the potential benefit of altering its built environment by utilizing digital twin principles because of its potential value to the stakeholders in the industry. "Everybody knows that digital transformation is happening," which is mentioned in the Gemini principles, reveals the UK's vision for using digitalization in the sector. Through various forms of government assistance, the government intends to back the transition comprehensively (ibid). The following is an outline of the four particular areas in which digital twin may be able to deliver value in the form of benefits:

- ➢ **Benefits to the economy:** Digital twin also have several benefits that are beneficial to the economy. Digital twin can generate economic growth and provide new employment possibilities if national productivity is significantly boosted, systemic solutions support the constructed environment, and enhance information management and security [78]. Also, the utilization of digital twin can result in building processes that are both more cost-effective and efficient, which increases economic production while simultaneously lowering the risk of project delays and cost overruns.
- ➢ **Positive effects on society:** the positive outcomes of implementing digital transformation in the building sector are numerous and must not be overlooked. The built environment and infrastructure are vital to day-to-day existence because they provide various benefits in various contexts [79]. Using digital twin can dramatically improve society by creating effectiveness-built environments which lead to the general populace's standard of living. In addition, it has the potential to deliver improved outcomes to consumers, such as increased accessibility, reduced energy costs, and overall quality of life. In addition, digital twin can promote transparency among stakeholders, thereby improving interactions among the many involved parties in the construction process.
- ➢ **Positive effects on the environment:** Digital twin have the potential to impact the surrounding environment positively. DTs have the potential to assist in lessening the environmental effects of construction projects and contribute to a more sustainable future for the built environment [77]. This would mean resource efficiency would be raised while waste and disturbance would be minimized.
- ➢ **Advantages to businesses:** the advantages of distributed technologies include creating business models and new market opportunities that use digital platforms and higher-performing infrastructure. This, in turn, might lead to a rise in profits and sales for active companies in the building sector [80]. The construction industry's value chain process, which comprises asset managers, investors, contractors, owners, consultants, and suppliers, may also profit from the utilization of digital twin. Digital twin, for instance, may assist in cutting down on the number of project delays and cost overruns, resulting in productive and lucrative construction projects.

3.7. *Challenges of implementing digital twin in the construction industry*

The implementation of digital twin in the construction industry faces several challenges [81-84]. These challenges can be categorized into five main areas: regulations, finance, management, technology, and awareness.

Regulatory challenges present significant hurdles for digital twin adoption. The construction industry often encounters regulatory barriers that can delay or complicate the implementation process. These obstacles may include compliance with existing standards, obtaining necessary approvals, and navigating complex legal frameworks. Government support plays a crucial role in overcoming these challenges by providing funding, establishing clear guidelines, and promoting policies that encourage the adoption of new technologies.

Financial considerations also pose substantial challenges. The initial investment costs for implementing digital twin technology can be significant, encompassing expenses for hardware, software, system integration, and personnel training. These high upfront costs may deter companies, particularly smaller firms, from adopting this technology despite its long-term benefits.

Management-related challenges are equally important. Effective management and decision-making are essential for successfully integrating digital twin technology into existing workflows. This involves strategic planning, resource allocation, and making informed decisions based on data provided by the digital twin. Additionally, managing the processes involved in implementation can be complex, requiring coordination between departments, ensuring data accuracy, and maintaining seamless operations during the transition period.

Technological challenges are at the forefront of digital twin implementation. The complexity of technology itself poses significant hurdles, with limited knowledge and expertise in this area hindering adoption. Issues related to system integration, data management, and cybersecurity further complicate the process. Moreover, there is often a shortage of experts with the necessary skills and experience to effectively implement and manage digital twin systems, leading to increased reliance on costly external consultants.

Awareness-related challenges also play a crucial role. Many stakeholders in the construction industry lack full awareness of the benefits and potential of digital twin technology. This knowledge gap can lead to resistance to change and a reluctance to invest in new technologies. Cultural and societal factors, including traditional work practices and a lack of digital literacy, can further impede adoption.

In addition, while digital twin technology offers significant potential for the construction industry, the challenges related to regulations, finance, management, technology, and awareness hinder its widespread implementation. Addressing these multifaceted challenges requires a coordinated effort from industry stakeholders, government bodies, and educational institutions to create an environment conducive to the adoption of digital twin technology. Overcoming these obstacles, the construction industry can harness the full potential of digital twins to improve efficiency, sustainability, and overall project outcomes.

3.8. Smart construction site

Site managers can leverage digital twin technology to optimize and streamline the building process on construction sites. By integrating virtual reality (VR), augmented reality (AR), Internet of Things (IoT) sensors, and radio frequency identification (RFID) tags, they can create a comprehensive digital replica of the site. This digital twin enables real-time monitoring, efficient supervision, and data-driven decision-making throughout the project lifecycle. The technology allows managers to visualize project progress in real-time, identify and address potential issues before they escalate, optimize resource allocation and scheduling, enhance safety measures through predictive analytics, and improve communication among stakeholders. By harnessing these digital tools, site managers can significantly improve project efficiency, reduce risks, and ensure more accurate project delivery [59]. Insights into various aspects of construction management can be gained through the application of advanced technologies. Data mining and process modelling techniques enable better understanding of material logistics, workflow management, and cost prediction. Unmanned aerial vehicles (UAVs) and other image-capturing devices can be employed to compare the actual construction process with the structural model [77,85]. This comparison provides a clearer picture of site progress. By integrating these technologies, project managers can enhance decision-making, optimize resource allocation, and improve overall project efficiency. The real-time data collected from these sources allows for proactive problem-solving and more accurate tracking of project milestones, ultimately leading to better control over timelines and budgets. Kifokeris & Koch [86], compiled a list of how blockchain technology may be integrated into various stages of the building process. Research has shown that using a digital model allows for safety concerns and potential risks in the workplace to be addressed in advance and reduced [77,85]. The construction workers and machine operators might benefit from mixed-reality simulation by identifying potential dangers related to the building stages and machine operations in advance.

The use of virtual reality (VR) to conduct training on less common aspects of construction, such as the assembly and disassembly of a tower crane, can bring the number of potential dangers encountered during training down to nearly nothing. Zhang et al. [87], stated that the location of the fall risks can be determined by using the BIM model, which is connected to an algorithm that detects hazards. This, in turn, ensures safety in the construction process. This indicates that gaps may exist between the real practice of construction activities and the stated assumptions in the model, thus requiring frequent algorithm updates. It was proposed by Boje et al. [77], that the digital twin paradigm should be adopted in addressing similar challenges through the linking of sensors to life activity for monitoring locations and workers' locations to identify and prevent potentially dangerous situations.

Greif et al. [88], developed a lightweight digital twin for industries that are not considered high-tech. The digital twin, together with sensors, are used to trace period, quantity and silos' usage, etc., by combining the obtained data with information relating to the restriction of the transportation of trucks and programmed alternation of silos. This is part of their case study for a bulk material provider. The digital twin and other algorithms are adopting AI to evaluate this information along with past and present facts. It then recommends the most effective courses of action and calculates dividends for each individual client based on this knowledge. Therefore, the operators have the option of either accepting the offered plan of action as is or making adjustments to it. The business can improve its predictability and ability to save money since it is always aware of its equipment's location and the overall fill amount. Kifokeris & Koch's [86] study suggests that when material, information and financial flows are seamlessly and transparently integrated within the supply chains, the logistics and success of the building project can be achieved. It is further argued that the requirement for accuracy and reliability on the various flows, in conjunction with the requirement for transparency and accountability, makes blockchains an appropriate technology for use as a validator of the aforementioned characteristics. According to Boje et al. [77], this helps various stakeholders better understand one another.

3.9. Built environment

The traditional perspective of the architectural, engineering, and construction (AEC) sectors has recently expanded to encompass facility management and operations [89]. This shift has fostered increased connectivity among key construction stakeholders, prompting a reconsideration of workflows across the entire delivery process and enabling a more comprehensive view of the built environment's lifecycle [90]. In research concerning digital twin in the built environment, the terms "AECO" (Architecture, Engineering, Construction, and Operation) or "AEC/FM" (Architecture, Engineering, Construction, and Facility Management) are commonly used to refer to the industry [91,92]. This terminology reflects the integrated approach that now characterizes the field.

Previous studies on digital twin in urban planning [93] have drawn attention to digital twin applications in the built environment [92]. Deng et al. [92], proposed an evolutionary ladder for the built environment, describing a progression from Building Information Modelling (BIM) to digital twin. BIM is supplemented by simulation, sensors, and artificial intelligence in this evolution to create more comprehensive and dynamic digital representations of physical structures. This evolution represents a significant advancement in how the industry conceptualizes and manages built assets, moving from static models to dynamic, data-driven representations that provide real-time insights and support more effective decision-making throughout a structure's lifecycle.

The ability of a structure to get to the digital twin ladder category facilitates communication and interaction with the established environments. In order for buildings to exchange real-time data, Deng et al. [92], claim that the digital twin of the future generation is scalable from individual buildings to multi-building communities and even to the level of an entire city [27]. On the other hand, the existing body of research simply discusses many unattainable features and significant ideas relating to the digital twin of the future generation. It has been discovered that the level of BIM is usually categorised into different phases, such as designing, structuring, and operating segments [94]. In contrast, the level of simulation gives room to assess the energy performance, which allows replication of upcoming building procedures [92]. The inclusion of IoT makes it possible to manage further the operations of energy and internal settings, deployment of space, and thermal comfort. This situation facilitates the proper monitoring of eminent dangers in the construction processes at the collective and individual levels. The processes of simulation and observation are made more accurate through the use of artificial intelligence, which helps to bring about real-time forecasts [95].

3.9.1. Buildings

Digital twin technology offers advantages over BIM, including enhanced information content and analytical capabilities [95]. It must also meet intelligence, integration, efficiency, and interoperability criteria. In the construction process, smart asset management at the building and infrastructure level represents a key digital twin application [96]. Scholars such as Deng et al. [92], Lu et al. [97], and Sepasgozar [27], have described the transition from Building Information Modelling (BIM) to digital twin in the context of asset management, activities and repairs. They note that BIM-based asset management has several limitations, including coordination of technical aspects, information detail, Level of Development (LOD), management of workflow and learning, and standardization of procedures, technologies, and development stages across disciplines [95].

Petri et al. [98], note that digital twin applications already exist for various phases of building construction, including design, construction, retrofitting, and maintenance, as well as for managerial and quality assurance purposes. Kaewunruen & Xu [99], describe a scalable digital twin framework for a university campus, encompassing managerial, construction, and societal levels. This framework includes data collection, transmission, digital modelling, and data-model integration layers. When examining a building's digital twin and related infrastructure, it's beneficial to consider it within the context of its neighbourhood and the broader city. This approach can provide insights into social and economic impacts and opportunities for improving city services like waste management and transportation. The service layer of dynamic building and city digital twin encompasses various aspects, including transportation, space utilization, health and safety, energy, event and failure predictions, and environmental management [99].

3.9.2. Cities

Researchers have proposed innovative approaches to intelligent building management and urban digital systems. These approaches highlight the potential of digital twin and IoT technologies to revolutionize urban planning, construction, and management. Yang et al. [100], advocate adopting IoT-based intelligent building management systems across various construction scenarios. Their proposal aims at creating energy-efficient buildings that contribute to sustainable city energy management within an IoT environment. Complementing this idea, Woodhead et al. [101], suggest that the central ecosystem component produced by an IoT network continues to function beyond the traditional completion of a construction project, implying a long-term, sustainable approach to building management and monitoring. The role of government in facilitating the adoption of these technologies is emphasized by Yang et al. [100]. They recommend prioritizing the elimination of regulatory bottlenecks and establishing rules for user privacy and security, which are crucial for improving investment incentives and fostering the development of appropriate technologies.

Lehner & Dorffner [102], demonstrate the scalability of the digital twin in urban contexts, showing that they can be implemented at various scales, from individual buildings to entire cities, providing value for both residents and stakeholders. Deren et al. [103], propose the creation of a city digital twin that combines human and artificial intelligence to enhance urban management procedures. In order to achieve effective energy management, sustainability, and optimization, there needs to be an interaction between urban digital twin structures supporting smart cities and various urban systems such as transportation, weather forecasting, and power networks. This integrated approach emphasizes the need for intelligent and sustainable strategies in built environment development.

4. Conclusion

Digital twins represent a paradigm shift in the construction industry, offering a comprehensive virtual representation of physical entities throughout their lifecycle. This study has explored the potential of digital twins to revolutionize construction practices, from individual structures to entire cities. The findings reveal that digital twins evolve alongside physical structures, enabling real-time monitoring, analysis, and optimization from planning through operations. Integrating with city-scale digital twins, building digital twins creates an interconnected ecosystem that enhances urban planning, construction logistics, and ongoing operations.

A key advantage of digital twins is their ability to accumulate vast amounts of data, facilitating informed decision-making and opening up new business models, particularly in operations and maintenance. This data-driven approach supports circular construction practices, promoting sustainability in the built environment. Furthermore, digital twins have the potential to drive the transition to Construction 4.0, enhancing digitalization and integration of advanced technologies across the industry. Despite their potential, the implementation of digital twins faces several challenges. The concept is still in its infancy in the construction sector, and its full potential may take time to realize. Industry-wide standards and protocols are needed for effective data sharing and interoperability. Additionally, concerns about personal privacy and data ownership must be addressed as data sharing increases.

Looking to the future, several research priorities emerge. These include developing advanced AI and ML algorithms for predictive capabilities, exploring blockchain for data security and traceability, and creating real-time data processing and analysis methods. There's also a need for improved human-digital twin interaction interfaces and the integration of sustainability metrics and lifecycle assessment tools. The industry is currently focusing on enhancing BIM and digital twin integration, developing robust IoT infrastructures for real-time data collection, and implementing digital twins for safety monitoring and management. Other areas of attention include optimizing energy consumption and supply chain efficiency, as well as exploring integration with smart city ecosystems. Digital twins represent more than technological advancement; they embody a new approach to business operations and collaborative, future-oriented thinking. As the construction industry continues to evolve, digital twins will play a crucial role in shaping more efficient, sustainable, and innovative built environments for future generations. Their potential to transform the entire lifecycle of construction projects, from planning to demolition, positions them as a key driver of innovation in the built environment sector.

CRediT authorship contribution statement

Taofeeq D. Moshood: Methodology, Conceptualization. **Gusman Nawanir:** Supervision. **Chia Kuang LEE:** Conceptualization. **Muhammad Ashraf Fauzi:** Visualization.

Declaration of competing interest

We confirm that the authors have declared no conflicts of interest pertaining to this research.

Data availability

No data was used for the research described in the article.

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